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Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia

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Abstract

In this letter we analyse the temporal development of physical population-driven water scarcity, i.e. water shortage, over the period 0 AD to 2005 AD. This was done using population data derived from the HYDE dataset, and water resource availability based on the WaterGAP model results for the period 1961–90. Changes in historical water resources availability were simulated with the STREAM model, forced by climate output data of the ECBilt–CLIO–VECODE climate model. The water crowding index, i.e. Falkenmark water stress indicator, was used to identify water shortage in 284 sub-basins. Although our results show a few areas with moderate water shortage (1000–1700 m^3/capita/yr) around the year 1800, water shortage began in earnest at around 1900, when 2% of the world population was under chronic water shortage (<1000 m^3/capita/yr). By 1960, this percentage had risen to 9%. From then on, the number of people under water shortage increased rapidly to the year 2005, by which time 35% of the world population lived in areas with chronic water shortage. In this study, the effects of changes in population on water shortage are roughly four times more important than changes in water availability as a result of long-term climatic change. Global trends in adaptation measures to cope with reduced water resources per capita, such as irrigated area, reservoir storage, groundwater abstraction, and global trade of agricultural products, closely follow the recent increase in global water shortage.

Keywords: water scarcity, water shortage, water stress, palaeo-water availability, global change, global water resources, population growth, late Holocene

S Online supplementary data available from stacks.iop.org/ERL/5/034006/mmedia

1. Introduction

Both human population and water resources are distributed unevenly across the globe. In many areas, densely populated regions do not overlap with those that are water rich. Due to the rapidly increasing population and water use per capita in many areas of the world, around one third of the world's population currently lives under physical water scarcity (e.g. Vörösmarty *et al* 2000, Alcamo *et al* 2003b, Oki and Kanae 2006). The physical water scarcity (or water resources scarcity) is not, however, the only scarcity that human populations face. A community, or a section of it, can also face water scarcity induced by political power, policies, and/or socio-economic relations, called social water scarcity (or second order water scarcity) (Ohlsson and Turton 1999). The 2006 Human Development Report, for example, concludes that water scarcity is not rooted in the physical availability of water, but in unbalanced power relations, poverty, and inequality (UNDP 2006).

Both physical and social scarcities highlight important aspects of water scarcity, and thus complement each other

(Ohlsson and Turton 1999). In this letter we concentrate on physical water scarcity, without diminishing the importance and role of social water scarcity. Physical water scarcity can be further divided into two main concepts: demand-driven scarcity (water stress) and population-driven scarcity (water shortage) (Falkenmark *et al* 2007). Demand-driven scarcity can be measured by examining how much water is being withdrawn from rivers and aquifers, known as the use-to-availability index (e.g. Vörösmarty *et al* 2000, Alcamo *et al* 2003b, Oki and Kanae 2006, Falkenmark *et al* 2007). The water shortage is related to the number of people that have to share each unit of water resources, and can be measured by using the water crowding index, also known as the Falkenmark water stress index (Falkenmark *et al* 1989, 2007). It should be noted that there are various categories of water demand, the main ones being water for industrial and municipal water supply; agriculture; and environmental needs. The role of environmental water requirements in physical water scarcity calculations has only recently been assessed, for example by Smakhtin *et al* (2004). Indices aiming to combine physical and social water scarcities include, for example, the water poverty index (Sullivan 2002, Sullivan *et al* 2003) and the social water stress index (Ohlsson 1998).

There have been various studies assessing global water scarcity from several different disciplines (e.g. Falkenmark and Lindh 1976, Falkenmark *et al* 1989, Raskin *et al* 1997, Ohlsson 1998, Alcamo *et al* 2000, Vörösmarty *et al* 2000, Oki *et al* 2001, Rosegrant *et al* 2002, Sullivan 2002, Alcamo *et al* 2003b, Arnell 2004, Smakhtin *et al* 2004, Oki and Kanae 2006, Alcamo *et al* 2007, Falkenmark *et al* 2007, Islam *et al* 2007). The majority of these studies have addressed how physical water scarcity may develop over time into the future, with a time span of a few decades ahead. The results have typically shown a rapid increase in the number of people under water stress or water shortage as a result of increasing population and/or water use, and in some cases as a result of climatic change (e.g. Vörösmarty *et al* 2000, Oki and Kanae 2006).

Despite the large number of water scarcity studies, no global assessment is available of how this trend has evolved over the past several centuries to millennia until the present day. Therefore, in this letter we analyse how global and regional water shortage (i.e. freshwater availability per person under a given threshold) has developed over the past 2000 years, by combining spatially explicit population data and output of a global climate model. The insights gained in this study help us to understand the dynamics and relative impacts of changes in population and water resources availability on water shortage. By examining where water shortage first developed, insights are derived into the reasons behind its historical development, enabling a comparison with large-scale adaptation measures and providing a better framework for interpreting future assessments.

2. Data and methods

Our research covers the time period from 0 AD to 2005 AD, using the water crowding index (Falkenmark *et al* 1989, 2007). The analyses were carried out at the geographical scale of the Food Producing Units (FPUs) of IFPRI (International Food Policy Research Institute) and IWMI (International Water Management Institute). These FPUs divide the world into 281 sub-basins, each sub-basin representing a hybrid between river basins and economic regions (Cai and Rosegrant 2002, Rosegrant *et al* 2002, De Fraiture 2007). These units are used because we assume that, for most of the time-slices, demand for water has been solved within such a hydro-political unit. It is acknowledged that for the most recent time-slices this may not be the case because of virtual water flows between FPUs as a result of increased international trade (see section 4). The original FPU map was slightly adjusted to include three regions (Siberia, Iceland, and Alaska) that were collectively grouped as a 'rest of the world' FPU in the original data. Furthermore, some low-lying (coastal) areas and small islands, which were originally not in any FPU, were merged with the closest FPU.

The water crowding index was originally developed for use in nation-scale analyses; we believe, however, that the FPU scale is large enough to support the assumptions behind the index thresholds. We aggregated the water shortage results at the FPU level to regional and global scales. Twelve regions were distinguished, based on the UN (United Nations) macro-regions of the world (UN 2000). Besides the aggregation of some regions, the most notable change to the original UN regions is that the South-Central Asia region was split in the following way: the more westerly countries were merged with West Asia to constitute the Middle East region, and the more centrally located Asian countries (former USSR states) were included in Eastern Europe (which includes Russia). The remaining countries form a separate South Asia region (figure 1). These changes were carried out because the South-Central Asia region in the UN classification is enormous and highly heterogeneous, whilst the sub-regions have been important separate entities in the past, both in terms of water resources and population.

2.1. Population

The analyses were carried out for ten time-slices. These time-slices were defined as those periods at which global population was approximately double the population of the previous time-slice (table 1). Population data for each time-slice were derived from the $5' \times 5'$ resolution ($\sim$9.3 km at the equator) global HYDE dataset (Klein Goldewijk 2005, Klein Goldewijk *et al* 2010). The global population distribution per FPU for each time-slice is presented in figure S1 in the online supplement (available at stacks.iop.org/ERL/5/034006/mmedia).

2.2. Water resources availability

In order to estimate water resources availability over the last two millennia, monthly temperature and precipitation output from the climate model ECBilt–CLIO–VECODE were used. ECBilt–CLIO–VECODE is a three-dimensional coupled climate model consisting of three components describing the atmosphere (ECBilt, Opsteegh *et al* 1998), ocean–sea–ice (CLIO, Goosse and Fichefet 1999), and land cover (VECODE, Brovkin *et al* 2002). The output used in this study was derived from a 9000 year long experiment forced by annually varying

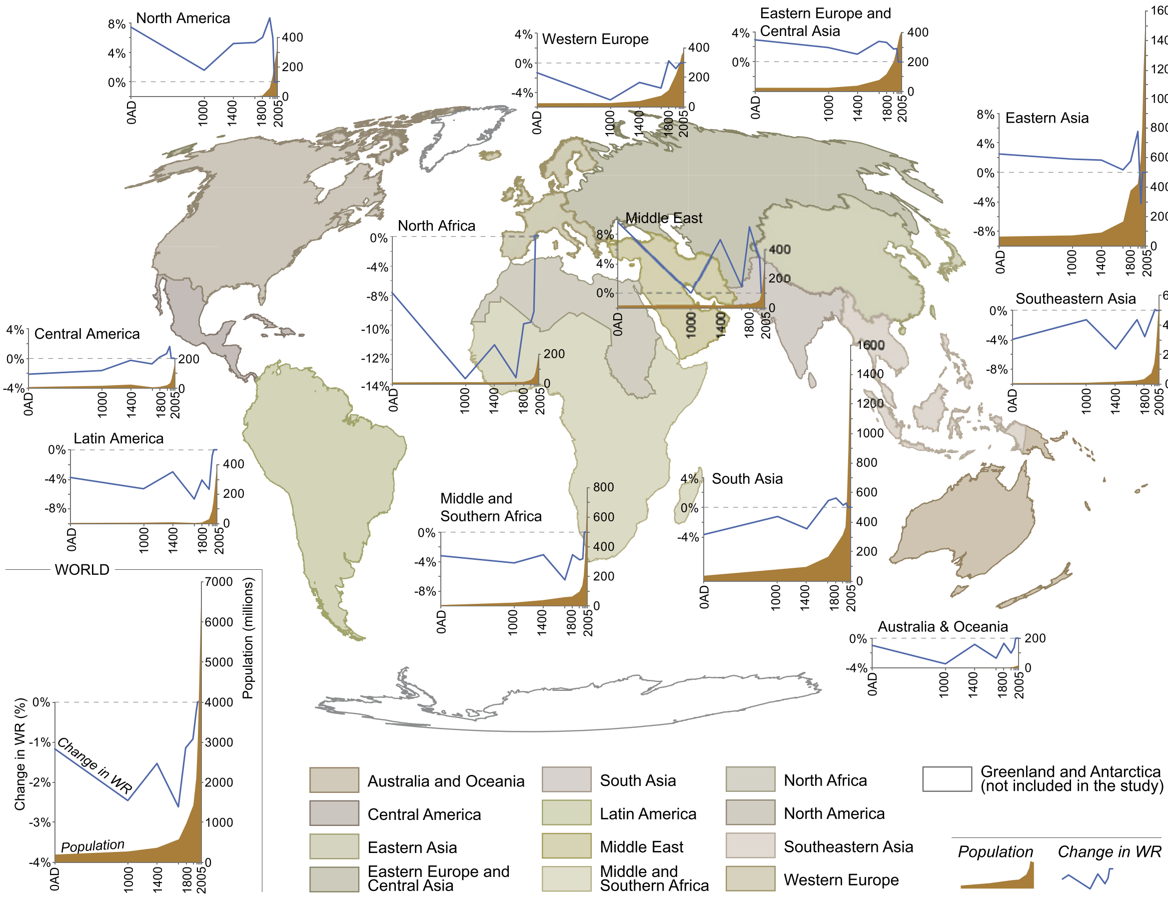

Figure 1. Regional (map) and global (lower left corner) population and water resources (WR) trends over the time period 0 AD–2005 AD. Population is shown by the filled area chart (right axis, in millions). Change in water resources is shown as percentage differences compared to the baseline (left axis).

Table 1. Total world population during the analysed time-slices and the percentage increase compared to the previous time-slice. Population data based on HYDE dataset (Klein Goldewijk 2005, Klein Goldewijk *et al* 2010).

	0 AD	1000	1400	1700	1800	1900	1940	1960	1980	2005
Population ($\times 10^9$)	0.19	0.27	0.36	0.57	0.96	1.62	2.28	3.02	4.45	6.55
% change		+41%	+35%	+59%	+68%	+69%	+41%	+32%	+47%	+47%

orbital parameters, and atmospheric greenhouse gas and sulfate aerosol concentrations (Renssen *et al* 2005).

The atmospheric output of the climate model has a spatial resolution of ca. 5.6° × 5.6°, but has been spatially downscaled and redistributed to a resolution of 0.5° × 0.5° for use in global hydrological studies (Aerts *et al* 2006, Renssen *et al* 2007, Ward *et al* 2007). In the study of Ward *et al* (2007), river discharges simulated with this climate model output were compared to geological proxy data over the last 9000 years. They found that long-term changes in the simulated discharges generally agree well with reconstructed changes based on geological data, giving confidence in the use of these data for the last two millennia.

The downscaled climate data were used to force the hydrological model STREAM (Aerts *et al* 1999), in order to derive estimates of water availability. STREAM is a grid based model that solves the water balance for each grid cell in order to estimate stream flows. In this study, only the water balance part of STREAM was used, which is based on the Thornthwaite–Mather equation (Thornthwaite and Mather 1955). The difference between the simulated actual evapotranspiration and precipitation in each grid cell was used as an indicator of water availability. This indicator was calculated for all time-slices at a spatial resolution of 0.5° × 0.5°, before being aggregated to the FPU scale.

Climatic conditions averaged over 50 years were used for each of the time-slices (e.g. for 1800 AD the average for the years 1775–1824 was used). As absolute values derived from climate model data are subject to model biases, only the proportional changes with respect to the baseline period (1961–90) were used. In order to estimate water availability in the historical time-slices, these proportional changes were multiplied with the more detailed estimate of current water availability for the baseline period, adopted from the WaterGAP 2.0 model (Alcamo *et al* 2003a). The WaterGAP 2.0 model results (GWSP Digital Water Atlas 2008) were used for the baseline period, i.e. 1961–90, and also for the 2005 estimate. The baseline water resources and percentage differences for each time-slice per FPU are presented in figure S2 of the online supplement (available at stacks.iop.org/ERL/5/034006/mmedia).

In this study we do not account for interannual variations of water resources availability or water consumption. Many climatic regions, ranging from arctic and boreal zones to monsoonal zones, may not be best described with annually averaged indicators. However, important short-term variations in interannual climate variability, such as the El Niño Southern Oscillation, are not well simulated by the climate model, and short-term natural forcings such as fluctuations in volcanic activity and sulfate aerosol concentrations are not included in the climate model parameterization used here (Renssen *et al* 2005). The incorporation of interannual variations warrants further attention in future methodological developments.

2.3. Water shortage calculations

The water crowding index was used for the water shortage calculations because it is widely used and is the only indicator for which the necessary data (i.e. water resources and population) are available for the long time period of this study. While useful for our long-term global scale assessment, the method has some distinct disadvantages that should be remembered when interpreting the results. These have been summarized by Rijsberman (2006), namely: (a) the large spatial scale averages hide important scarcity at smaller scales; (b) the method does not take into account the infrastructure that modifies the availability of water to users; and (c) it does not reflect the important variations in water demand among countries due to, for instance, differences in lifestyle and climate. Being a physical water scarcity indicator, the water crowding index does not include the aspects of, for instance, social, political, and/or economic power relations, or government policies regarding access to water. Furthermore, the index does not consider so-called virtual water flows, which have recently had a growing influence on water use around the globe (e.g. Chapagain *et al* 2006, Oki and Kanae 2006).

Although the use of FPUs as spatial unit is justified for our research (see above), the spatial heterogeneity is an issue for further discussion. As pointed out by Rijsberman (2006), the water crowding index does not take into account the important local differences within the spatial unit used. Once the threshold indicating water shortage in an FPU in question is exceeded, the calculations result in all of the people living in that FPU being classified as experiencing water shortage. This is normally not the case; often one or several sectors of water users or sections of a community will have better access to water than others.

A particular challenge in the method is how to handle urban areas, which, according to UN (2010), already house over half of the world's population. Urban areas typically import the bulk of their food and other water-consuming commodities from rural areas, which are increasingly far away. The consideration of water quality, too, is absent from most of the water stress analyses. This is despite the fact that water quality problems tend to accumulate into areas and regions where water is also scarce (Varis 2007b). In urban areas, the water quality concern is of particular importance.

However, since we are working at a global and regional scale, and examining long-term trends rather than short-term variability, we believe that the methods and data used provide sufficiently detailed results to capture the evolution of regional and global water shortages. The thresholds and definitions for different levels of water shortage used in this study follow the thresholds of Falkenmark *et al* (1989), and terms for two main groups are updated according to Falkenmark *et al* (2007), which are as follows:

- Moderate water shortage: available water resources are 1000–1700 m^3/capita/yr.
- Chronic water shortage: <1000 m^3/capita/yr. This class is here further divided as follows:
  - * High water shortage: 500–1000 m^3/capita/yr.
  - * Extreme water shortage: <500 m^3/capita/yr.

3. Results

While the analyses were carried out at the FPU scale, we present our results mainly at the regional and global scale. Only water scarcity results from 1800 onwards are presented at the FPU scale, to illustrate where and when water shortage first occurred and how it developed across the globe. Population, water resources availability, and water shortage data at the FPU scale are available for all time-slices in figures S1–S3 of the online supplement (available at stacks.iop.org/ERL/5/034006/mmedia).

3.1. Population and water resources trends over the study period

In general, population development shows similar trends across the different regions (figure 1). However, there are some important differences. For example, the so-called New World (Australia and Oceania, Central America, Latin America, and North America) experienced much more growth between the years 1700 and 1900 compared to other regions, where population began to increase earlier. From the year 1900 onwards, the highest proportional population growth has been in Central America, Latin America, Middle and Southern Africa, and the Middle East. The population continued to increase until 2005 in all regions, but the annual growth rates have decelerated to below 2% in most regions (except Middle and Southern Africa, Middle East, North Africa, and South Asia). The population growth rate averaged over the 20th century has been lowest (<1%) in Eastern Europe and Central Asia, and Western Europe.

The modelled changes of water resources availability through time are rather stable in most regions, varying within ±5% when compared to the baseline. Many of these relatively stable regions experienced a dryer climate before the present; only Eastern Europe and Eastern Asia were wetter (figure 1). Three regions experienced larger than ±5% changes in available water resources compared to the baseline; in the Middle East and North America more water was available

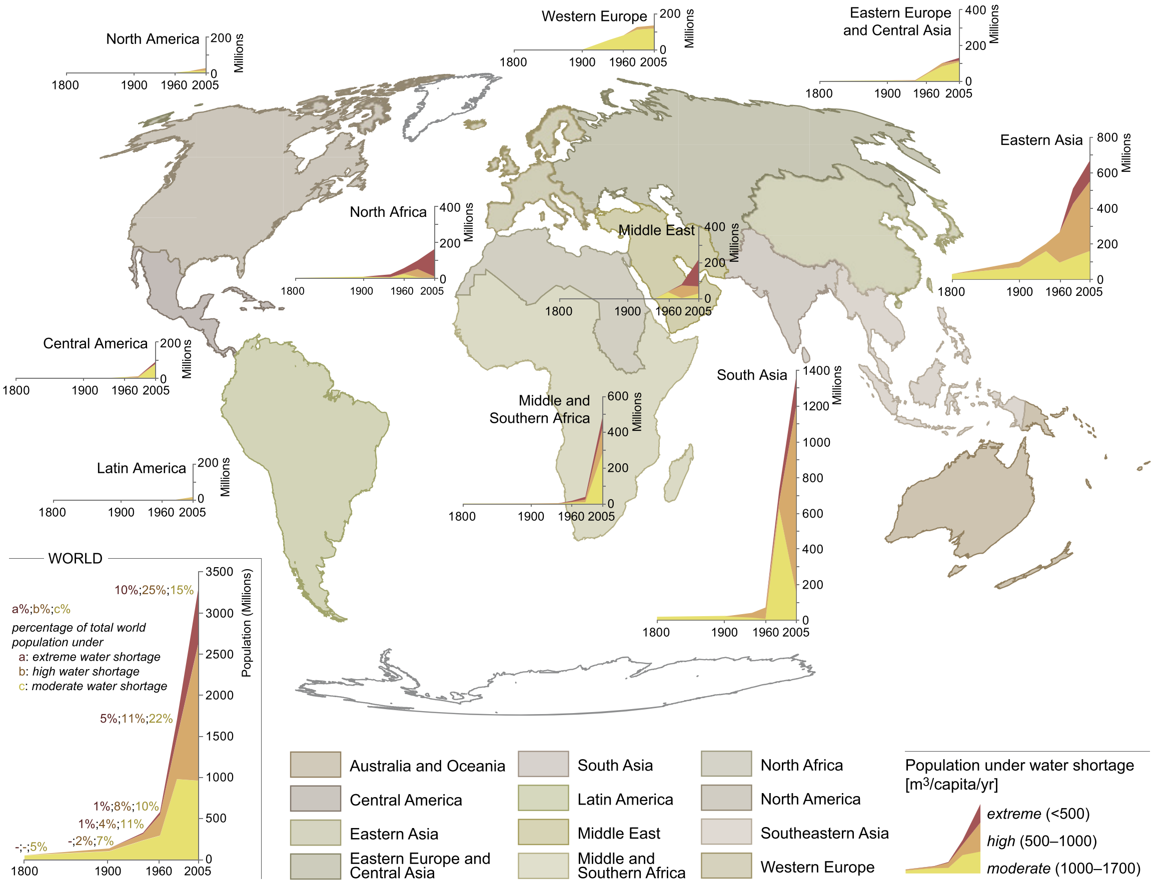

Figure 2. Regional (map) and global (lower left corner) trends of population under moderate, high, and extreme water shortage over the time period 1800–2005. Note: the analyses for Southeastern Asia and Australia and Oceania show no water shortage during the analysis period. Greenland and Antarctica are not included in the analysis.

Table 2. Global results for population under water shortage, differentiated in three categories, over the whole study period. The unit $m^3/c/y$ stands for m^3/capita/yr. The numbers in brackets give cumulative values of the number of people living below the upper threshold limit of each category.

	Population under water shortage (millions)			Percentage of total world population		
	<500 $m^3/c/y$	500–1000 $m^3/c/y$	1000–1700 $m^3/c/y$	<500 $m^3/c/y$	500–1000 $m^3/c/y$	1000–1700 $m^3/c/y$
0 AD	0	0	0.1 (0.1)	—	—	—
1000	0	0	4.6 (4.6)	—	—	2% (2%)
1400	0	0	0.1 (0.1)	—	—	—
1700	0	0	5.7 (5.7)	—	—	1% (1%)
1800	0	0	48 (48)	—	—	5% (5%)
1900	0	32 (32)	99 (131)	—	2% (2%)	7% (9%)
1940	15	77 (92)	229 (321)	1%	4% (5%)	11% (16%)
1960	34	250 (284)	287 (571)	1%	8% (9%)	10% (19%)
1980	213	497 (710)	969 (1679)	5%	11% (16%)	22% (38%)
2005	656	1640 (2296)	951 (3247)	10%	25% (35%)	15% (50%)

during the past two millennia compared to present, while in North Africa the situation was opposite (figure 1).

3.2. Water shortage

As measured with the water crowding index, the first signs of water shortage appear from about 1800 AD, by which time the number of people under moderate water shortage exceeded 40 million (ca. 5% of the world population at that time (table 2; figure 2)). Prior to that time, our results show only small regions with moderate water shortage in North Africa (figure S3 available at stacks.iop.org/ERL/5/034006/mmedia). Water shortage commenced in earnest from 1900 onwards, after which the number of people under shortage increased rapidly (table 2; figure 2). The amount of people experiencing water shortage grew first in Eastern Asia and parts of Africa, followed by the Middle East and then South Asia (figure 3). The year 1960 can be seen as a clear turning point; after that

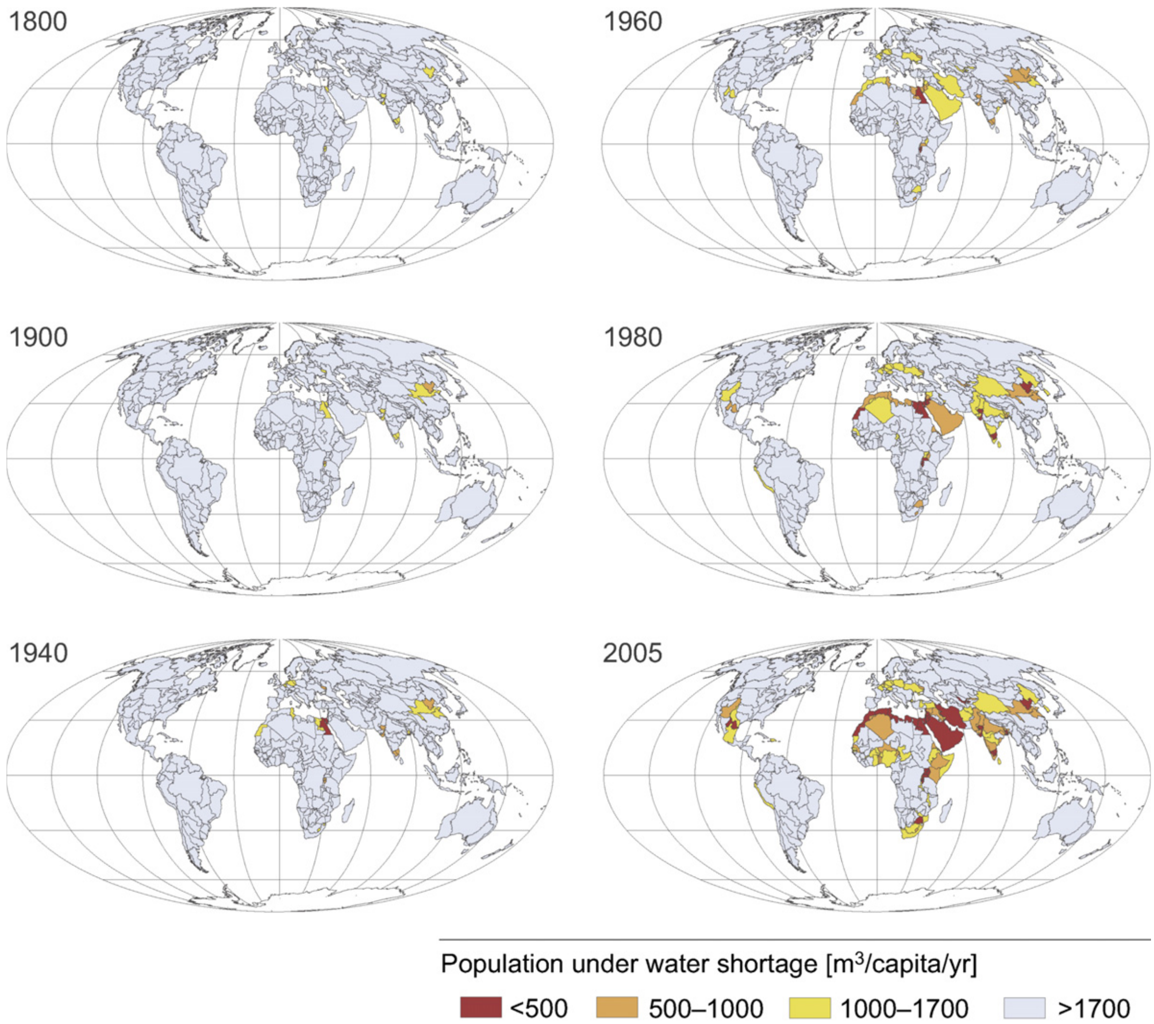

Figure 3. Water shortage mapped for each FPU for the time period 1800–2005.

date the population experiencing water shortage soared in each category (table 2; figure 2). In 2005, the total population living under water shortage exceeded three billion, which is approximately half of the world population. Of these people, 2.3 billion (i.e. 35% of the world population) lived under chronic water shortage (<1000 m^3/capita/yr) (table 2).

The differences in trends of water shortage over the last two hundred years between regions are considerable (figure 2). For instance, in Eastern Asia and North Africa, over 20% of the population have been under some level of water shortage since 1900, while in the Middle East this point was not reached until 1960, and in South Asia slightly later. Thereafter, the number of people under water shortage in South Asia and the Middle East increased rapidly. By 2005, South Asia was the region with the highest proportion (91%) of people experiencing water shortage. Other regions where over half of the population experiences some form of water shortage (<1700 m^3/capita/yr) are North Africa (81%), the Middle East (76%), and Middle and Southern Africa (66%). Central America and Eastern Asia may soon join them, with 2005 figures as high as 49% and 42% respectively. The four regions in which over half of the population already lives under water shortage are the same regions in which annual population growth rates are still over 2% (see section 3.1), indicating that water shortage will probably continue to increase rapidly in these regions in the future. Water shortage is especially severe in North Africa and the Middle East, where over half of the population is under extreme water shortage (figure 2).

When assessing the number of people under water shortage, five regions stand out, namely Eastern Asia, South Asia, North Africa, Middle East, and Middle and Southern Africa. Over the last two hundred years, these regions have accounted for 77–100% of the total population under some form of water shortage, and 96–100% of the total population under extreme water shortage.

4. Discussion

We examined the relative impacts of water resources availability and population on water shortage using a linear regression analysis for the total population, total water resources, and the amount of people under water shortage per region for each time-slice ($n = 120$; $R^2 = 0.80$). The results show that the influence of population is about

Table 3. Comparison of the global population (billions) under water scarcity between different studies. Results are shown for different scales (grid, sub-basin, FPU, basin, and country level), reference years, and water scarcity indices. R_{ws} stands for 'use-to-availability index', and FPU for 'food production units'.

	Total population (billions)										
Study:	[a]	[b]	[c]	[d]	[e]	[e]	[f]	[f]	[f]	[g]	[h]
Ref. year	2005	1995	2000	1995	1995	1995	1995	1995	1995	1995	2000
Resolution	FPU	Sub-basin	Grid	Grid	Grid	Country	Grid	Country	Basin	Grid	Grid
<1000 m^3/c/y	2.3	1.4	1.8–3.1	1.6							
$R_{ws} > 0.4$				2.3	1.8	0.5	1.7	2.2	2.7	2.1	2.4

[a] This study. [b] Arnell (2004). [c] Islam *et al* (2007). [d] Alcamo *et al* (2007). [e] Vörösmarty *et al* (2000). [f] Oki *et al* (2001). [g] Alcamo *et al* (2003b). [h] Oki and Kanae (2006).

four times as large as the influence of the available water resources (standardized beta coefficients being 0.97 and −0.23 respectively).

We compared our results for the year 2005 with other recent studies on physical water scarcity (Vörösmarty *et al* 2000, Oki *et al* 2001, Alcamo *et al* 2003b, Arnell 2004, Oki and Kanae 2006, Alcamo *et al* 2007, Islam *et al* 2007). However, such a comparison is not straightforward, as many studies use a different index to the one used in our study, namely the use-to-availability index (e.g. Oki and Kanae 2006). This index estimates the proportion of renewable water resources that is used by humans. In table 3 we show results using the two indices, whereby we compare estimates of population under chronic water shortage (<1000 m^3/capita/yr) with estimates of population with a high water stress ($R_{ws} > 0.4$), as done previously by Oki and Kanae (2006) and Alcamo *et al* (2007). Note that the reference years vary between the studies (1995, 2000, 2005), as do the spatial resolutions (from grid to country level). Nevertheless, the comparison shows that our results are well in line with the findings of other studies, and fall within the variation of those (table 3).

Over time, humans have taken various measures to optimize the use of available water (water mobilization or adaptation measures). Three major strategies to do so during the 20th century include: the construction of reservoirs to handle blue surface water variability (e.g. Oki and Kanae 2006); the irrigation of cropland to reduce green water deficit (e.g. Freydank and Siebert 2008); and abstraction of groundwater to alleviate blue water deficiency (e.g. Shah *et al* 2007). Moreover, increased international trade of agricultural products can also be seen as a way to alleviate water scarcity, virtually importing water from the region where the crops were produced. As historical calculations of such virtual water flows are not available, we use world trade of agricultural products as an indicator, thereby assuming that virtual water flows expanded along with expanding world trade (see, for example, statistics by WTO 2006).

We compared trends of world reservoir capacity (Chao *et al* 2008), global area equipped for irrigation (Freydank and Siebert 2008), use of groundwater (Shah 2005, Shah *et al* 2007), and global trade of agricultural products (WTO 2006), to the trends of the number of people experiencing water shortage during the last century (figure 4). This comparison shows that the trends of the adaptation strategies are similar to those of population-driven global water shortage. However, more scrutiny is necessary to quantify these relationships, and to allow for an assessment of their implications, since a similar growth pattern does not necessarily mean a causal relationship.

For the abstraction of groundwater, there is a strong geographical overlap with water shortage, most notably in India (Shah *et al* 2007), suggesting that they are indeed related. For the area under irrigation there is also a good link in some regions (Siebert *et al* 2005). However, there are also other important conditions, such as climate and income level (e.g. there is relatively little irrigated area in Africa). With respect to reservoirs, the timing of reservoir building in Asia and Africa is well in line with the water shortage trend (Chao *et al* 2008). Reservoirs are, however, often built for other purposes (mainly hydropower) as well. Agricultural trade, and corresponding virtual water flow, seems mainly driven by economic development, as the majority of the trade occurs between high income regions with low levels of chronic water shortage (Aksoy 2005). However, Yang *et al* (2003) found that the demand for cereal import increases exponentially with decreasing water resources after a certain water shortage threshold, supporting the notion that trade has been used to combat water shortage in Asia and Africa.

Since physical water scarcity is estimated to continue to grow despite these measures (e.g. Vörösmarty *et al* 2000, Oki and Kanae 2006, Alcamo *et al* 2007), the discussion should also include the accompanying 'soft' adaptation measures (i.e. non-structural), such as water governance, water pricing, and increasing water use efficiency (e.g. Kundzewicz *et al* 2007). In this regard, the political, economic, social, and governance systems should be the primary focus. This entails facets such as the fee structure of water services, recycling approaches, regulation policies, improvements in water distribution networks, irrigation technologies, and so forth, and above all the management of water quality and environmental integrity. Crucial to all of these measures is the human component. The technological and institutional developments underlying the various ways to manage water by non-structural means are all preconditioned and linked in one way or another to the 'human dimension' of the water sector, and they funnel to the concepts of water governance, water management, water policy, and water's role in societal and economic development (Saleth and Dinar 1997, Ohlsson and Turton 1999, Schreiner *et al* 2002, UNDP 2006, Barnes 2009, Varis and Abu-Zeid 2009).

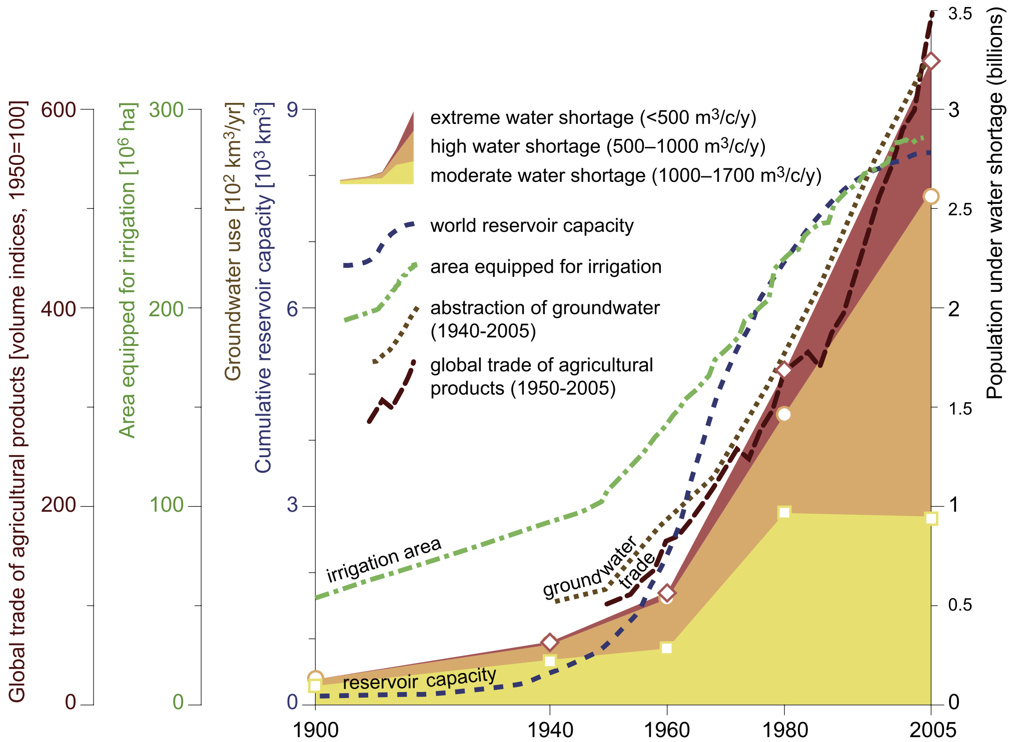

Figure 4. Comparison of population under water shortage with: world reservoir capacity (source: Chao *et al* 2008); area equipped for irrigation (source: Freydank and Siebert 2008); abstraction of groundwater (source: Shah 2005, Shah *et al* 2007); and global trade of agricultural products (as an indicator of virtual water flows) (WTO 2006) for the period 1900–2005. Note: data for groundwater use are only available for the period 1940–2005, and global trade data for the period 1950–2005.

Finally, it should be noted that the methodology used in this study makes use of threshold values as defined by Falkenmark *et al* (1989, 2007) in order to quantify the amount of people experiencing water shortage; the absolute results are sensitive to the choice of such thresholds. A simple sensitivity analysis shows that when the threshold values are changed by 20%, the absolute amount of people under water stress changes by 30%–60%, depending on the water shortage level considered. As the same threshold values are used in all time-slices, the relative change in the amount of people under water stress is not affected by this sensitivity. Keeping the thresholds constant over time implicitly assumes that the effective use of water resources does not change over time. It is not possible to include changes in water use efficiency in this study, as no data are available to estimate global changes in efficiency over the last 2000 years. However, there is an increasing amount of data available for the last 100 years (e.g. Wisser *et al* 2010), and thus future research could increase understanding of both water demand and water use for the past century.

5. Conclusions

We analysed the trend in water shortage over the past 2000 years at the scale of food production units (FPUs) by using the water crowding index approach of Falkenmark *et al* (1989). Moderate water shortage first appeared around 1800, but it commenced in earnest from about 1900, when 9% of the world population experienced water shortage, of which 2% was under chronic water shortage (<1000 m^3/capita/yr). From 1960 onwards, water shortage increased extremely rapidly, with the proportion of global population living under chronic water shortage increasing from 9% (280 million people) in 1960 to 35% (2300 million) in 2005. Our analyses show that the effects of changes in population on water shortage over this time period are roughly four times as important as changes in water availability due to long-term climatic change. Currently, the most widespread water shortage is in South Asia, where 91% of the population experiences some form of water shortage. The most severe shortage is in North Africa and the Middle East, where 77% and 52% of the total population lives under extreme water shortage (<500 m^3/capita/yr) respectively.

In response to the prospect of water shortage, measures have generally been taken to increase water availability (e.g. building dams, abstracting groundwater). Our study reinforces the view that there are already several regions in which such measures are no longer sufficient, as there is simply not enough water available in some regions. This problem is expected to increase in the future due to increasing population pressure (e.g. UN 2009), higher welfare (e.g. Grübler *et al* 2007), production of water intensive biofuels (e.g. Varis 2007a, Berndes 2008), and climatic change (e.g. Vörösmarty *et al* 2000, Oki and Kanae 2006, Alcamo *et al* 2007). Consequently, there will be an increasing need for non-structural measures, focusing on increasing the efficiency of water use, lowering water use intensity in regions with water shortages, reforming the economic structure of countries or entire regions, and optimizing virtual water flows from regions without shortage to regions with shortage. Research on water shortage and scarcity should, therefore, continue to extend towards the inclusion and scrutiny of concepts of water governance, water management, water policy, environmental integrity, and water's role in societal and economic development.

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